REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
30-Sep-2008

2. REPORT TYPE
REPRINT

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
SEISMIC SOURCE SCALING AND DISCRIMINATION IN DIVERSE TECTONIC ENVIRONMENTS

5a. CONTRACT NUMBER
FA8718-06-C-0024

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
62601F

5d. PROJECT NUMBER
1010

5e. TASK NUMBER
SM

5f. WORK UNIT NUMBER
A1

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10. SPONSOR/MONITOR'S ACRONYM(S)
AFRL/RVBYE

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
AFRL-RV-HA-TR-2008-1088

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for Public Release; Distribution Unlimited.

Boston University[1], Weston Geophysical Corporation[2], and Lawrence Livermore National Laboratories[3]

13. SUPPLEMENTARY NOTES
Reprinted from: Proceedings of the 30th Monitoring Research Review – Ground-Based Nuclear Explosion Monitoring Technologies, 23 – 25 September 2008, Portsmouth, VA, Volume I pp 525 - 534.

14. ABSTRACT The objectives of this study are to improve low-magnitude (concentrating on M2.5-5) regional seismic discrimination by performing a thorough investigation of earthquake source scaling using diverse, high-quality datasets from varied tectonic regions. Local-to-regional high-frequency discrimination requires an estimate of how earthquakes scale with size. Walter and Taylor (2002) developed the Magnitude and Distance Amplitude Corrections (MDAC) method to empirically account for these effects through regional calibration. The accuracy of these corrections has a direct impact on our ability to identify clandestine explosions in the broad regional areas characterized by low seismicity. Unfortunately our knowledge at small magnitudes (i.e., mb < ~4.0) is poorly resolved, and source scaling remains a subject of on-going debate in the earthquake seismology community. Recently there have been a number of empirical studies suggesting scaling of micro-earthquakes is non-self-similar, yet there are an equal number of compelling studies that would suggest otherwise. It is not clear whether different studies obtain different results because they analyse different earthquakes, or because they use different methods. Even in regions that are well studied, such as test sites or areas of high seismicity, we still rely on empirical scaling relations derived from studies taken from half-way around the world at inter-plate regions. We investigate earthquake sources and scaling from different tectonic settings, comparing direct and coda wave analysis methods that both make use of empirical Green's function (EGF) earthquakes to remove path effects. Analysis of locally recorded, direct waves from events is intuitively the simplest way of obtaining accurate source parameters, as these waves have been least affected by travel through the earth. But finding well recorded earthquakes with "perfect" EGF events for direct wave analysis is difficult, limits the number of earthquakes that can be studied. We begin with closely-located, well-correlated earthquakes. We use a multi-taper method to obtain time-domain source-time-functions by frequency division. We only accept an earthquake and EGF pair if they are able to produce a clear, time-domain source pulse. We fit the spectral ratios and perform a grid-search about the preferred parameters to ensure the fits are well constrained. We then model the spectral (amplitude) ratio to determine source parameters from both direct P and S waves. We analyze three clusters of aftershocks from the well-recorded sequence following the M5 Au Sable Forks, NY, earthquake to obtain some of the first accurate source parameters for small earthquakes in eastern North America. Each cluster contains a M~ 2, and two contain M~3, as well as smaller aftershocks. We find that the corner frequencies and stress drops are high (averaging 100 MPa) confirming previous work suggesting that intraplate continental earthquakes have higher stress drops than events at plate boundaries. We also demonstrate that a scaling breakdown suggested by earlier work is simply an artifact of their more band-limited data. We calculate radiated energy, and find that the ratio of Energy to seismic Moment is also high, around 10^{-4}. We estimate source parameters for the M5 mainshock using similar methods, but our results are more doubtful because we do not have an EGF event that meets our preferred criteria. The stress drop and energy/moment ratio for the mainshock are slightly higher than for the aftershocks. Our improved and simplified coda wave analysis method uses spectral ratios (as for the direct waves) but relies on the averaging nature of the coda waves to use EGF events that do not meet the strict criteria of similarity required for the direct wave analysis. We have applied the coda wave spectral ratio method to the 1999 Hector Mine mainshock (*Mw* 7.0, Mojave Desert) and its larger aftershocks, and also to several sequences in Italy with M~6 mainshocks. The Italian earthquakes have higher stress drops than the Hector Mine sequence, but lower than Au Sable Forks. These results show a departure from self-similarity, consistent with previous studies using similar regional datasets. The larger earthquakes have higher stress drops and energy/moment ratios.

15. SUBJECT TERMS
Seismic characterization, Seismic propagation, Seismic discrimination

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					Robert J. Raistrick
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			**19b. TELEPHONE NUMBER** *(include area code)*
UNCLAS	UNCLAS	UNCLAS	SAR	10	781-377-3726

SEISMIC SOURCE SCALING AND DISCRIMINATION IN DIVERSE TECTONIC ENVIRONMENTS

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Sponsored by Air Force Research Laboratory

Contract No. FA8718-06-C-0024
Proposal No. BAA06-70

ABSTRACT

The objectives of this study are to improve low-magnitude (concentrating on M2.5-5) regional seismic discrimination by performing a thorough investigation of earthquake source scaling using diverse, high-quality datasets from varied tectonic regions. Local-to-regional high-frequency discrimination requires an estimate of how earthquakes scale with size. Walter and Taylor (2002) developed the Magnitude and Distance Amplitude Corrections (MDAC) method to empirically account for these effects through regional calibration. The accuracy of these corrections has a direct impact on our ability to identify clandestine explosions in the broad regional areas characterized by low seismicity. Unfortunately our knowledge at small magnitudes (i.e., $m_b < \sim4.0$) is poorly resolved, and source scaling remains a subject of on-going debate in the earthquake seismology community. Recently there have been a number of empirical studies suggesting scaling of micro-earthquakes is non-self-similar, yet there are an equal number of compelling studies that would suggest otherwise. It is not clear whether different studies obtain different results because they analyse different earthquakes, or because they use different methods. Even in regions that are well studied, such as test sites or areas of high seismicity, we still rely on empirical scaling relations derived from studies taken from half-way around the world at inter-plate regions.

We investigate earthquake sources and scaling from different tectonic settings, comparing direct and coda wave analysis methods that both make use of empirical Green's function (EGF) earthquakes to remove path effects. Analysis of locally recorded, direct waves from events is intuitively the simplest way of obtaining accurate source parameters, as these waves have been least affected by travel through the earth. But finding well recorded earthquakes with "perfect" EGF events for direct wave analysis is difficult, limits the number of earthquakes that can be studied. We begin with closely-located, well-correlated earthquakes. We use a multi-taper method to obtain time-domain source-time-functions by frequency division. We only accept an earthquake and EGF pair if they are able to produce a clear, time-domain source pulse. We fit the spectral ratios and perform a grid-search about the preferred parameters to ensure the fits are well constrained. We then model the spectral (amplitude) ratio to determine source parameters from both direct P and S waves. We analyze three clusters of aftershocks from the well-recorded sequence following the M5 Au Sable Forks, NY, earthquake to obtain some of the first accurate source parameters for small earthquakes in eastern North America. Each cluster contains a M~ 2, and two contain M~3, as well as smaller aftershocks. We find that the corner frequencies and stress drops are high (averaging 100 MPa) confirming previous work suggesting that intraplate continental earthquakes have higher stress drops than events at plate boundaries. We also demonstrate that a scaling breakdown suggested by earlier work is simply an artifact of their more band-limited data. We calculate radiated energy, and find that the ratio of Energy to seismic Moment is also high, around 10^{-4}. We estimate source parameters for the M5 mainshock using similar methods, but our results are more doubtful because we do not have an EGF event that meets our preferred criteria. The stress drop and energy/moment ratio for the mainshock are slightly higher than for the aftershocks.

Our improved and simplified coda wave analysis method uses spectral ratios (as for the direct waves) but relies on the averaging nature of the coda waves to use EGF events that do not meet the strict criteria of similarity required for the direct wave analysis. We have applied the coda wave spectral ratio method to the 1999 Hector Mine mainshock (M_w 7.0, Mojave Desert) and its larger aftershocks, and also to several sequences in Italy with M~6 mainshocks. The Italian earthquakes have higher stress drops than the Hector Mine sequence, but lower than Au Sable Forks. These results show a departure from self-similarity, consistent with previous studies using similar regional datasets. The larger earthquakes have higher stress drops and energy/moment ratios.

We perform a preliminary comparison of the two methods using the M5 Au Sable Forks earthquake. Both methods give very consistent results, and we are applying the comparison to further events.

OBJECTIVES

The objectives of this study are to improve low-magnitude regional seismic discrimination by performing a thorough investigation of earthquake source scaling using diverse, high-quality datasets from varied tectonic regions. Local-to-regional high-frequency discrimination requires an estimate of how earthquakes scale with size. Walter and Taylor (2002) developed the MDAC method to empirically account for these effects through regional calibration. The accuracy of these corrections has a direct impact on our ability to identify clandestine explosions in the broad regional areas characterized by low seismicity. Unfortunately, our knowledge at small magnitudes (i.e., $m_b < \sim 4.0$) is poorly resolved, and source scaling remains a subject of on-going debate in the earthquake seismology community. Recently, there have been a number of empirical studies suggesting scaling of micro-earthquakes is non-self-similar (e.g., Kanamori et al.,1993, Abercrombie, 1995, Mayeda and Walter, 1996, Mori et al., 2003, Stork and Ito, 2004, Izutani and Kanamori, 2001, yet there are an equal number of compelling studies that would suggest otherwise (e.g., McGarr, 1999, Ide and Beroza, 2001, Imanishi et al., 2004, Prieto et al., 2004. It is not clear whether different studies reach different conclusions because they use different datasets and scaling varies with location, or because they use different methods. Sonley and Abercrombie (2006) show that small variations in the commonly used methods can lead to significant differences in results. Even in regions that are well studied, such as test sites or areas of high seismicity, we still rely on empirical scaling relations derived from studies taken from half-way around the world at inter-plate regions.

In summary, we address the following problems.

1. Do different studies obtain different results because they use different methods, or because they analyse different data sets? We will investigate whether coda and direct wave methods applied to the same datasets provide the same scaling.
2. Is scaling dependent upon the tectonic setting? We will investigate earthquakes from different tectonic settings and depth ranges, using the same coda and direct wave methods.
3. There have been few studies in intra-plate areas where seismicity is low and/or in regions where a clandestine test might occur. The MDAC method currently assumes earthquake source scaling that was derived exclusively from the western United States. Can we extrapolate or transport results from one region to others, or must we calibrate to each specific region? We will analyse earthquakes from both interplate (e.g., California) and intraplate (e.g., Eastern North America) regions to specifically address this question.

RESEARCH ACCOMPLISHED

Our approach to obtaining improved source parameters for small earthquakes focuses on the direct and coda wave methods: to improve and investigate them both, and then to apply them to diverse data sets.

Locally recorded, direct waves from events have been least affected by travel through the earth, and so are thought to be the best candidate for obtaining accurate source parameters. But there are only a limited number of earthquakes that are recorded locally, by sufficient stations to give good azimuthal coverage. Even fewer of these have an equivalently well recorded, very closely located smaller earthquake that meets the stringent criteria required to be a good EGF to remove path effects. This EGF method is the preferred one for isolating the source, but concern about the quality of the EGFs is a major source of uncertainty in studies that use these methods. In contrast, coda waves average radiation from all directions so single-station records should be adequate and previous work suggests that the requirements for the EGF event are much less stringent. It is thus ideal in regions with sparse stations and events so that most events are only well-recorded by a single station. Our approach is to:

1. Develop an easy to apply coda wave spectral ratio method to obtain source parameters for large groups of earthquakes
2. Identify the mainshock – EGF earthquake pairs that meet stringent criteria for selecting the EGF, and obtain source parameters from the direct waves for this subset of events.
3. Use the direct wave results to confirm, and if necessary correct, the coda wave results.
4. Apply these methods to data sets from a range of tectonic environments.
5. Determine the implications of the determined source scaling results for both coda calibration and regional discrimination using MDAC and other similar means of source and path-corrected discriminants.

So far we have developed improved coda wave and direct wave methods that we will apply consistently to all the data sets. The new spectral-ratio method developed in this study makes the coda method much easier and simpler to apply, greatly extending the number of earthquakes that can be studied. The coda wave approach was published by Mayeda et al. (2007). We have applied the coda wave methods to several aftershock sequences in Italy

(Malagnini and Mayeda, 2008, Malagnini et al., 2008), and have begun to apply it in eastern North America. In the direct wave study, we have investigated the effects of the various analysis choices commonly made, and also developed criteria for assessing the quality of a particular EGF event. We have performed a very detailed direct wave EGF analysis of aftershocks of the Au Sable Forks earthquake (eastern North America), and obtained some of the best constrained source parameters for earthquakes in this tectonic setting. The direct wave analysis method and results are described by Viegas et al. (2008).

Application of Coda Spectral Ratio Method: Apennines and Central California shear zone:

Earlier in our study, we developed an EGF method using coda waves, and showed that it is stable and provides reliable results even if the EGF events have different focal mechanisms to the larger earthquakes, and are separated by as much as 25 km (published as Mayeda et al., 2007). We compared coda spectral ratios to direct spectral ratios and found that the coda wave ratios are much more stable, with little variation from station to station. We then applied the method to the Hector Mine (M7.1, 1999) earthquake and six large aftershocks in the central California shear zone. We now combine this method with a grid-search algorithm taken from MDAC (Walter and Taylor, 2002) to find the best fitting parameters for a group of earthquakes, as well as the fitting uncertainties. This algorithm is used to analyze network-averaged, coda-based spectral ratios, computed between the main event of a sequence, and all its available aftershocks.

We apply the coda spectral-ratio method to two sequences of earthquakes in the Apennines, an intra-plate setting (Figure 1), and again to the Hector Mine sequence to obtain consistent results, with error bars, for comparison. The San Giuliano sequence (2002) was characterized by two main events (both M_w 5.7, and with similar, almost pure strike-slip mechanisms, depths, and source kinematics, see Vallee and Di Luccio, 2005). The main earthquakes were followed by a relatively small number of aftershocks at depths ranging between 10 and 20 km. Because of the low-level of observed ground shaking, both the main events were believed to be low-stress drop. The largest earthquake in the Colfiorito sequence (1997–1998, see Amato et al., 1998) was M_w6.0. The M_w7.1 Hector Mine earthquake was followed by a large aftershock sequence and we analyze six of the larger aftershocks, recorded at broadband stations.

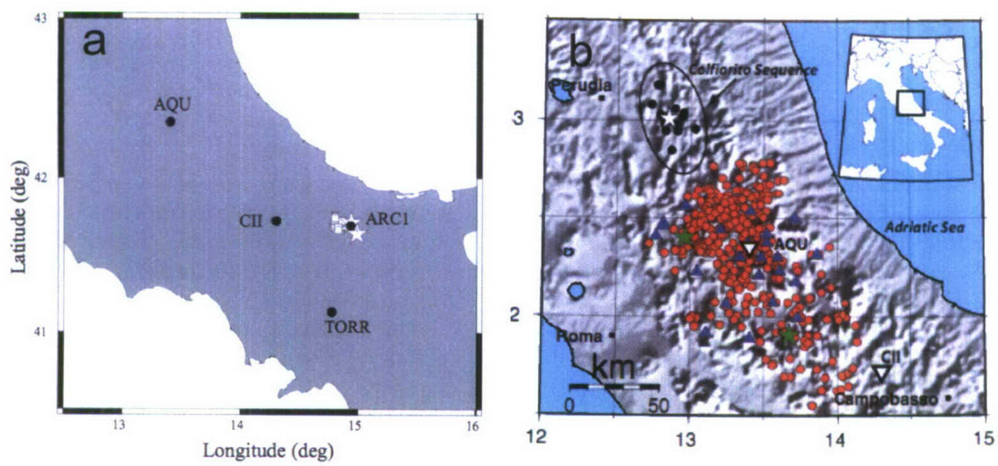

Figure 1: Maps of (a) the San Giuliano and (b) the Colfiorito earthquake sequences. In (a) main shocks are indicated by white stars, aftershocks by white squares, and seismic stations by black solid circles. In (b) the earthquakes used are shown as black dots, and the stations as inverse white triangles.

We follow the method described by Mayeda et al. (2007) to calculate coda spectral-ratios and fit them to obtain source parameters including seismic moment (M_0), corner frequency (f_c), and stress drop ($\Delta\sigma$). For each of the three seismic sequences analyzed in this study, the number of aftershocks is limited through a quality control performed on the available spectral ratios. Specifically, we define a 1.8 minimum bandwidth for each usable spectral ratio (log units, i.e., the ratio of the largest frequency to the lowest one must be larger than 63), and a minimum differential magnitude of 1.0. After this first screening, each average ratio is visually inspected to assure that bad data are not included in the analysis. Standard errors are obtained by looping through the entire set of available spectral ratios, using the technique described by Mayeda et al. (2007) in an iterative fashion. A different spectral ratio is used on

each iteration for the calculation of the scaling properties of the main shock, with respect to the specific aftershock to which the ratio is referred. At the end of the procedure, specific distributions are thus available for all the estimated parameters and so their standard errors can be given.

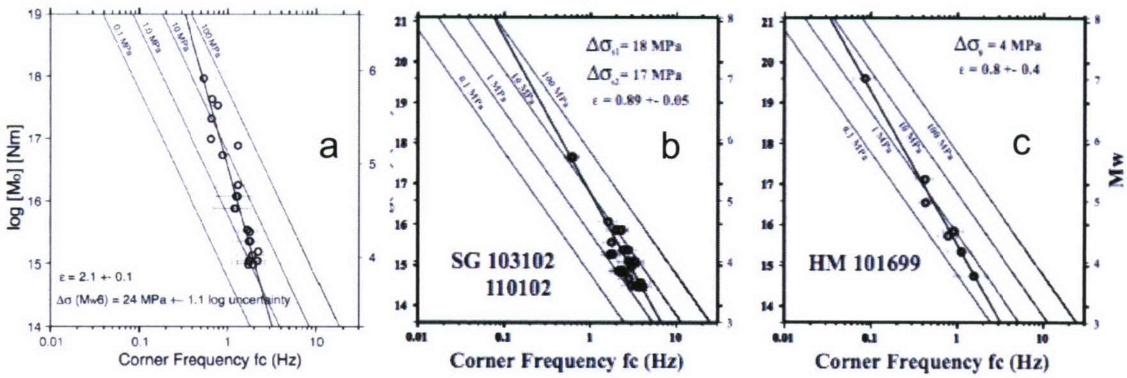

Figure 2. Coda wave method results. Corner frequencies and stress drops for the (a) Colfiorito, (b) San Giuliano, and (c) Hector Mine earthquake sequences. All three sequences appear to show non-self similar scaling. The two intra-plate sequences have higher average stress drops than the Hector Mine earthquake sequence.

Figure 2 shows the results of the analysis for the three sequences. The average stress drops of the two intraplate sequences (Figure 2a and b) are systematically higher than those of the Hector Mine sequence in a region with higher strain rate. None of the three sequences exhibit self-similar (constant stress drop) source scaling. The Colfiorito sequence shows a gradual decrease in stress drop with decreasing moment. The other two sequences are consistent with the same trend, or could also simply result from the largest earthquake having a higher stress drop than the aftershocks.

Development of Direct Wave EGF Method and Application to Eastern North America:

Analysis of earthquakes in stable, intraplate, low-seismicity regions is important to characterize these regions, but it is hard because of the sparcity of earthquakes and stations, and hence useful data. Relatively little is known about earthquake sources in intraplate regions, and often relationships based on minimal data, or simply extrapolated from interplate regions are assumed due to lack of local information. For example, Somerville et al. (2002) use the recordings of only three moderate-sized earthquakes to propose source scaling relationships for earthquakes in the Northeastern USA and other stable continental regions. Their results imply that earthquakes in the Northeastern USA have relatively high stress drops. This result was confirmed by Shi et al. (1998) who analysed almost 50 small earthquakes from the region. Their study included eight EGF pairs (Shi et al., 1996), but mostly individual earthquakes. They also found a decrease in stress drop with seismic moment, at small magnitudes (< M~3). This may indicate that earthquake source scaling is different in this intraplate region, or else may represent a limit to the resolution as was found earlier in the San Andreas Fault plate boundary region (e.g., Abercrombie and Leary, 1993). Shi et al (1998) were mostly limited by data availability to using regional recordings at single stations, and so to frequencies less than about 25 Hz.

In the last decade there has been a significant increase in the number of broadband seismic stations deployed in eastern North America, leading to a growing number of well-recorded earthquakes (M2-5). On April 20, 2002 an earthquake of magnitude M_L 5.3 occurred in the northeastern Adirondack Mountains, Seeber et al. (2002). Following the mainshock, Lamont-Doherty Earth Observatory deployed digital portable seismographs to monitor aftershocks. The portable network spanned an area about 24 by 20 km with an average inter-station spacing of 4 – 6 km, smaller than the average source depth. Between April 22 and November 2002, 74 small aftershocks were detected and located in the epicental area of the mainshock. These data (200 samples/s) represent the best recorded earthquakes in the region to date, and so provide an unprecedented opportunity to investigate source parameters in this intraplate setting.

We calculate the source parameters using two methods commonly applied to direct waves recorded at local stations: spectral modeling of the individual three-component P and S waves (e.g., Abercrombie, 1995), and the EGF method

(e.g., Mori and Frankel, 1990, Abercrombie and Rice, 2005). Both methods require data with a high-frequency content to work well. Many studies consider the EGF method superior as it corrects for all path and site effects by using a smaller, collocated earthquake as an EGF. The EGF method cannot be used to calculate the seismic moment of the earthquakes, but this is the most reliable information that can be obtained from the individual spectral analysis. Using cross-correlation we identify three clusters of earthquakes with very similar waveforms that include the largest aftershocks recorded by the portable network. All clusters include an M≥2, and a number of M1-2 earthquakes, and two clusters also each include an M≥3 earthquake. We model the spectra obtained by dividing the spectrum of the large earthquake by the smaller one. We also use regional recordings (100 samples/s) to analyze the M5 mainshock using the largest aftershock (M3.7) as the EGF. These earthquakes are closely located, and the deconvolution produces a source time function, but clearly have a different focal mechanism, and so do not meet the criteria for selecting an EGF that we describe below. Unfortunately, no aftershocks well recorded regionally meet these criteria so we use the largest aftershock, and interpret our results with caution.

It is not clear in many studies how close the EGF events are to a perfect Green's function. They are typically too small to obtain focal mechanisms, and the location uncertainties are larger than the preferred separation between events. We select only events that are located within the uncertainties of the large event, and have a high degree of waveform similarity, determined by cross-correlation. As a further test, we transform all the spectral ratios back to the time domain, and we only use pairs where we are able to resolve a clear source pulse. If a source time function is observable in this way, then it demonstrates that the phase components of the spectra are also very similar. This test is similar to the investigation performed by Mori and Frankel (1990) to determine how closely located earthquake pairs must be for the EGF method to work well. Multitaper methods have long been preferred to calculate source spectra and spectral ratios as they better represent the frequency content of the waveforms than do cosine and other tapers (e.g., Park et al., 1987). Unfortunately, until recently multitaper codes only worked with amplitude spectra and so could not be used to perform the complex deconvolution. We use the multitaper approach recently developed by Prieto et al., (2008) to perform the full complex deconvolution so that we can use the same frequency analysis to obtain both the best spectra and retrieve the source time functions.

We correct the velocity seismograms for the instrument response, and then select time windows of 5 s (regional) and 0.75 s (local) that start 0.1 seconds before the P or S wave onset. We use the multitaper method from Prieto et al. (2008) to calculate the Fourier displacement amplitude spectra. We use seven weighted tapers and a time-bandwidth-product of 4. The algorithm also removes a noise peak centered at 60 Hz, if present. Figure 3 shows an example of the seismograms, spectra, and EGF analysis for two events in one cluster.

We first calculate source parameters using the individual spectra, to determine the seismic moments, and also to compare the results of this standard method with that of the preferred EGF method. Before modeling the individual amplitude spectra, we re-sample them on a logarithmic scale, so that the fits were not biased to the high frequencies. We use samples at intervals of $10^{0.02}$, and the amplitude value was the average of all the points in a neighborhood of $\pm 10^{0.01}$. We fit the displacement amplitude spectra with the omega-square source model with the sharper corner preferred by Boatwright (1980) and Abercrombie (1995) to obtain the seismic moment, corner frequency and attenuation Quality factor (Q). The travel time is calculated from the S minus P time. The displacement spectra are fit at bandwidths with signal to noise ratio above 3. We perform a grid search around the preferred parameters to investigate the uncertainties within a range of variance of fit of +5%. We take the mean of all available components and stations to calculate the final value. Following Abercrombie (1995) we assume the circular fault model of Madariaga (1976) to calculate source radius (r), and the solution of Eshelby (1957) for a circular crack to calculate stress drop ($\Delta\sigma$). We calculate the radiated seismic energy (E_S) by integrating the velocity-squared spectrum, using the data within the available bandwith and the best fitting model to extend the frequency range (Abercrombie 1995).

We then apply the EGF method to the earthquakes in the clusters we identified. We use the same amplitude spectra to calculate spectral ratios between the different events, and we also use the extension of the multitaper method to the complex spectra to deconvolve the spectral ratios back to the time domain and so obtain estimates of the source time functions. We only continued the analysis if we obtained a clear source pulse, justifying our choice of EGF event (see Figure 3). We resample the spectral ratios on a logarithmic scale (in the same way as the individual spectra) and we model the spectra ratios using the same source model as the individual spectra. We use reasonable constraints on the fitting parameters as a further constraint on the use of EGF pairs and ratios (Figure 3). We then calculate source parameters from the spectral fitting as for the individual spectra.

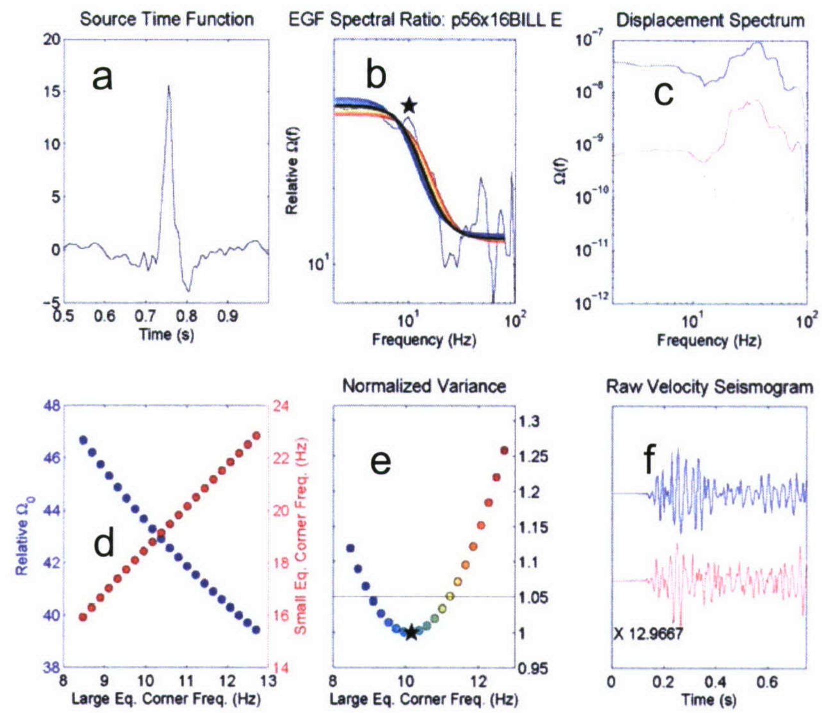

Figure 3: Example of analysis to obtain parameters from spectral ratio. (a) shows the source time function, (b) the spectral ratio of the displacement spectra (black) and the fits (rainbow colors) within 5% increase of variance of the minimum. The star marks the corner frequency of the minimum variance fit. (c) the displacement spectra of the two earthquakes (solid) and their preceding noise (dotted). (d) the long period amplitude of the ratio, and corner frequency of small earthquake, as the corner frequency of the large earthquake is varied, (e) the variance of the fit, colors are the same as in (b), and (f) the raw P wave seismograms with the relative amplification of the smaller (red) earthquake used in the plot. In this example a M~3 is divided by a M~2, and the seismograms are highly correlated, we have a clear source time function, a tight parabola in variance, and two well resolved corner frequencies

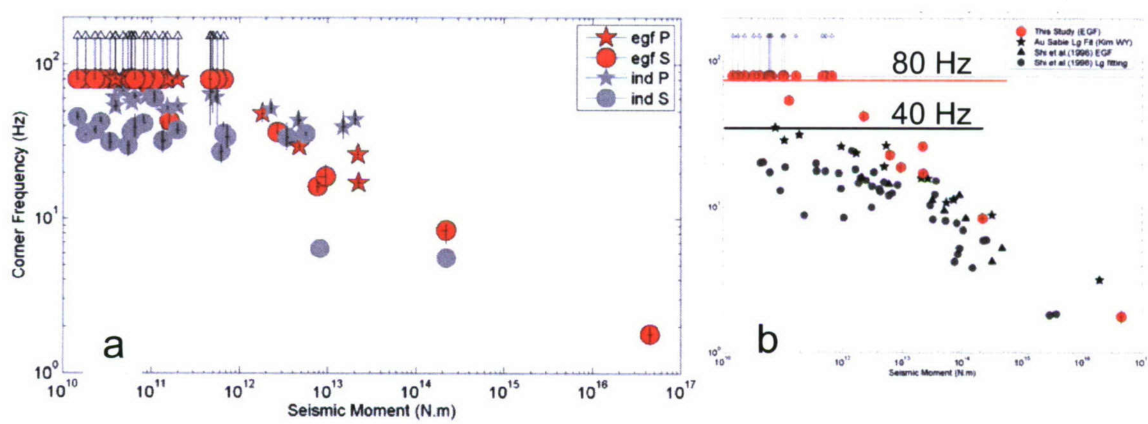

Figure 4. Corner frequency measurements and comparison with previous work in eastern North America. (a) compares the EGF and individual fitting results for P and S wave measurements, averaged for each earthquake. The agreement is good for larger magnitudes, but the individual method underestimates the corner frequency when it nears the maximum frequency limit. (b) Comparison of our results with those of Shi et al. (1998). The concluded that scaling broke down below M_0~10^{13} Nm, but comparison with our results implies that this is an artifact of their lower maximum frequency limit (40 Hz), and use of only individual fitting results for the smaller earthquakes.

The smallest earthquakes have corner frequencies that are clearly outside the available bandwidth (>80 Hz). The EGF results are preferred because of their better correction for path and site effects. The individual fitting tends to underestimate the corner frequencies (and hence the stress drops) as they get close to the high frequency limit (Figure 4). The high stress drops we obtain are consistent with the previous studies which find relatively high stress drops for intraplate regions such as eastern North America. They are consistent with the results of Shi et al (1998) for their EGF events, but we do not see a breakdown in constant stress drop scaling at lower magnitudes, suggesting that this was an artifact of the limited bandwidth available to Shi et al. (Figure 4).

We obtain relatively high stress drops and apparent stress (proportional to the ratio of E_S/M_0), compared to previous studies, mostly in interplate environments (Figure 5). This is consistent with the hypothesis that faults in

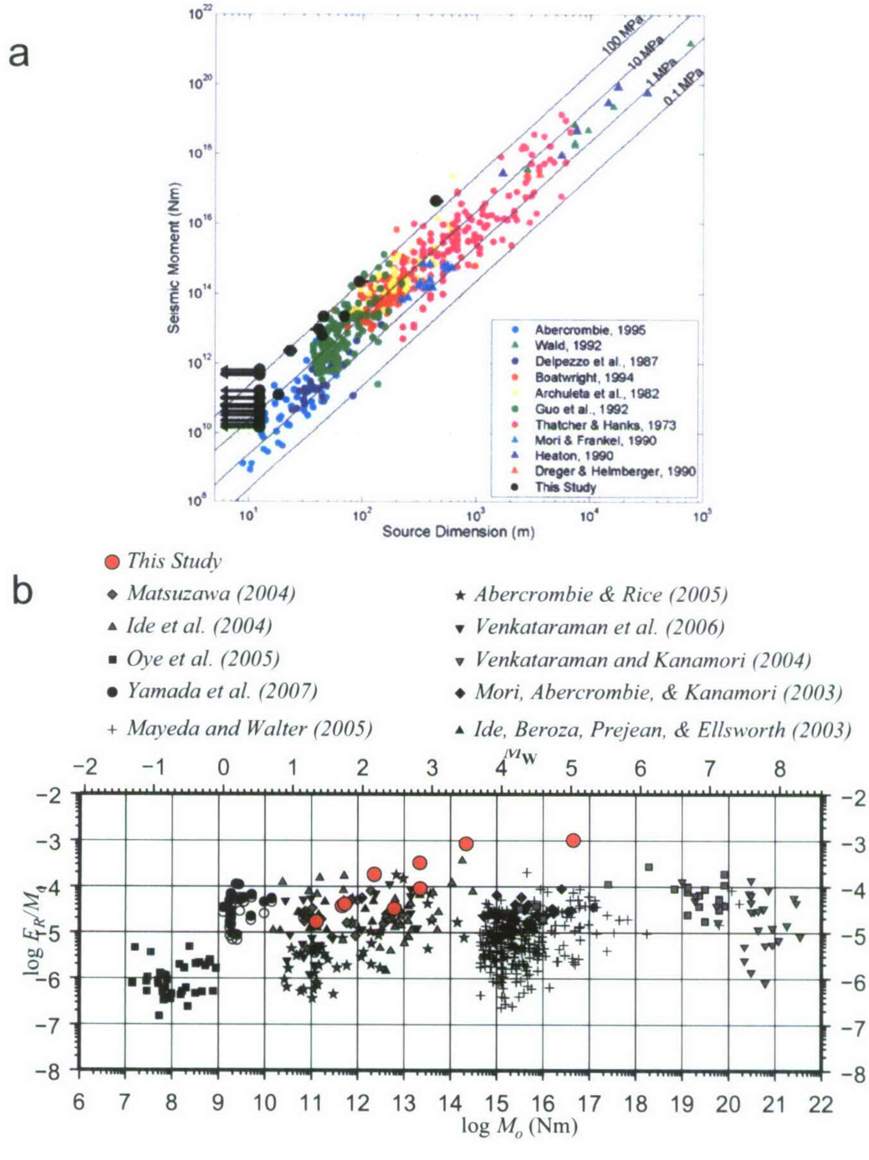

Figure 5. Comparison of source parameters for the Au Sable Forks earthquake sequence with those from other studies, mostly at plate boundaries. The Au Sable Forks earthquakes have relatively high stress drops (a) and ES/M0 ratios (b) compared to those of earthquakes from continental plate boundary settings. (a) is after Tomic et al. (2008), the source model corrected version of Abercrombie and Leary (1993), and (b) is after Ide and Beroza (2001) and Yamada et al. (2007).

intraplate settings with lower strain rates, lower cumulative deformation, and longer healing time between ruptures will be stronger than faster moving faults at plate boundaries. Our results also show some gradual decrease in stress drop and apparent stress with decreasing moment. Unfortunately, this is largely dependent on the uncertainties in the values for the two largest earthquakes. These are less reliable because of the lack of an acceptable EGF event.

Coda Wave Analysis in Eastern North America:

We calibrate the coda waves at regional broadband stations in eastern North America using the Au Sable Forks mainshock and largest aftershock. We then calculate the spectral ratio, and fit it, and obtain very similar results for corner frequency and stress drop to those for direct waves. This is encouraging, but we want to perform further testing because (1) we use the same EGF for both direct wave and coda wave, so we do not compare the effect of less stringent criteria for choosing EGF for the coda wave method, and (2) the EGF used for the direct wave work does not meet our preferred criteria. When we analyze the aftershocks of this, and other, sequences, we will compare using preferred EGFs for the direct wave analysis with using EGFs for the coda wave analysis that do not meet the requirements for the direct waves.

CONCLUSIONS AND RECOMMENDATIONS

In summary, we have developed our preferred analysis methods for the direct and coda waves. We have applied the methods to different sequences of earthquakes, and begun to compare the methods directly. The next step is to study more earthquake sequences and rigorously compare the methods.

The coda wave analysis finds relatively high stress drops for two earthquake sequences in the intraplate setting of the Apennines, compared to earthquakes in the higher strain rate setting of western North America. These studies also show the non self-similar scaling that has been observed in previous studies using coda waves.

The direct wave analysis of the aftershocks of the Au Sable Forks earthquake confirms that earthquakes in eastern North America have very high stress drops (10–100 MPa). They also show that the sharp decrease in stress drop with decreasing moment at low magnitudes reported by Shi et al. (1998) is most likely an artifact of the limitations of their data. The stress drops and energy show some possible diversion from self-similar scaling, but uncertainties about the parameters for the largest earthquakes could be the cause.

The first preliminary comparison of the coda and direct wave methods for the Au Sable Forks earthquake (M5) finds very similar results by the two methods, which is encouraging but cannot be interpreted as a rigorous test.

The next stage of our analysis is to perform a more rigorous comparison of the coda and direct wave methods. We will perform coda wave analysis on the aftershocks of Au Sable Forks and other earthquakes of eastern North America. For the direct wave study, we will use earthquakes with EGFs that meet out preferred criteria. For the coda wave study, we will use the same EGF earthquakes, and also ones that clearly do not meet the direct wave criteria. We will also perform both direct and coda wave analyses on several sets of Californian earthquakes for tectonic comparison. In this way we will determine whether the results of the simpler, easier to apply, coda-wave ratio method really do represent average source parameters, or whether any corrections or systematic biases need to be considered.

ACKNOWLEDGEMENTS

We thank Luca Malagnini for his contribution to the work on coda spectral ratios, German Prieto for developing the multi-taper code to obtain time-domain source time functions, and Won-Young Kim for providing the portable aftershock recordings of earthquakes in eastern North America, and information about his regional wave analysis.

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